

Faint star counts in the near-infrared

J.B. Hutchings, P. B. Stetson

Herzberg Institute of Astrophysics, NRC of Canada,

Victoria, B.C. V8X 4M6, Canada

john.hutchings@nrc.ca

A. Robin

Observatoire de Besançon, BP 1615, F-25010 Besançon cedex, France

annie@obs-besancon.fr

T. Webb

Dept of Astronomy, University of Toronto, Canada

webb@astro.utoronto.ca

Received _____; accepted _____

ABSTRACT

We discuss near-infrared star counts at the Galactic pole with a view to guiding the NGST and ground-based NIR cameras. Star counts from deep K-band images from the CFHT are presented, and compared with results from the 2MASS survey and some Galaxy models. With appropriate corrections for detector artifacts and galaxies, the data agree with the models down to $K \sim 18$, but indicate a larger population of fainter red stars. There is also a significant population of compact galaxies that extend to the observational faint limit of $K = 20.5$. Recent Galaxy models agree well down to $K \sim 19$, but diverge at fainter magnitudes.

Subject headings: Galaxy: halo; infrared radiation; instrumentation: high angular resolution; galaxies: evolution

1. Introduction

The projected sky density of faint stars and galaxies in the near infrared (NIR) at high Galactic latitudes is of interest for guiding telescopes and NIR cameras. In the case of large telescopes it is important to choose the field of view to assure high probability of finding a guide star, while minimising the size and cost of the guiding system. As these instruments can guide on stars down to $K \sim 18$ or fainter, it is necessary to know the densities at those and fainter magnitudes, since at present we have no NIR catalogues that go this deep.

The lowest density of stars occurs at the Galactic poles, where they are predominantly M-type stars at these magnitudes. Thus, for guide signal purposes we need NIR star counts and catalogues to allow for best guiding, regardless of the wavelengths of observation. The all-sky 2MASS survey is limited to about $K=16$; while the HST guide star catalogue goes to fainter V magnitudes, the NIR flux of these stars is not well known, since $V-K$ for M stars is in the range of 5 magnitudes, and changes steeply with spectral type.

In this paper we report on star counts from deep K -band images from the CFHT IR camera, and also review other models and estimates down to $K \sim 20$.

2. Data

We have two deep fields from the CFHTIR camera, taken with K band filter. The total area covered is about 107 sq arcmin of sky. The fields are at Galactic coordinates $l=177^\circ$, $b=-50^\circ$, and $l=97^\circ$ and $b=60^\circ$. The fields were observed as follow-up observations of objects detected at $850\mu\text{m}$ in two fields of the Canada-UK Deep Submillimeter Survey to identify near-IR counterparts of very luminous, high-redshift, dusty galaxies.

The data were taken over four nights in January of 2001. The $b=-50^\circ$ field is a mosaic of four contiguous individual pointings of integration times from 2.7 to 3.3 hours. The

b=60° field is a mosaic of 3 overlapping pointings of varying depth. Two pointings were observed for 1 hour and one pointing for 4 hours. The weather was generally worse in the latter and the image was therefore not as deep as the integration time would suggest. The final mosaic images have FWHM close to 0.9", and have fairly uniform depth of exposure.

The observations were processed using basic NIR techniques. After first removing the bias signal, sky flats were created from the program data. For each program image, the (dithered) images which bracketed it in time were combined to form a sky flat. This sky flat was normalized and used to correct its corresponding image. The remaining sky signal (a DC offset and low order structure at a few percent) was then removed from all the images using the IRAF task BACKGROUND, and the individual images calibrated and combined to form the final image. The HST/NICMOS faint standards were used for calibration.

Object detection and photometry was done with DAOPHOT (Stetson 1987) and ALLSTAR (Stetson and Harris 1988). Point-spread functions were derived from well-exposed stars in the images, and least-squares fits of these model PSFs were carried out to obtain relative brightnesses of the detected objects. The SHARP and CHI indices provided by ALLSTAR were used to identify obvious galaxies and image defects. The conversion from instrumental Data Numbers in the image to stellar magnitude used a photometric zero point for the entire mosaic of images based on the data processing and observing details.

We obtained 2MASS K-band data for an overlapping region of sky in one of the CFHT fields (2MASS did not cover the other). The photometric zero point was checked by the 2MASS magnitudes for 10 bright stars, and found to be consistent to within 0.1 magnitudes. The magnitude/sharpness plots are shown in Figure 1. The exercise also allowed an interesting comparison of the same piece of sky with CFHT and 2MASS (see Figure 2).

From the two mosaic fields, we have magnitudes for some 2000 objects down to $K \sim 20.5$ (see Figure 1). The image quality is not exceptional for CFHT but allows useful star-galaxy separation. For the cameras and telescopes in development at present, we are interested in guiding only down to about $K=18$. At this magnitude, we have very good completeness and star-galaxy separation (checked by inspection).

Completeness goes to much fainter than this, although the asymmetrical distribution of sharpness index among the fainter objects strongly suggests we are seeing a population of compact galaxies that overlap the star distribution fainter than about $K=18$. The limits of the star distribution are sketched in, symmetrically about zero sharpness index value. The negative sharpness points below the limits are noisy pixels. The boundary was established at faint magnitudes from the distribution of magnitude errors with magnitude for the negative sharpness index values, because of the extra population in the positive sharpness distribution. This was verified by inspection of the images of objects near the boundary. The boundary was also checked for positive sharpness objects by inspection. We also note that the boundary values we have derived are very typical of ALLSTAR results from many other investigations.

To obtain a star count free of compact galaxy contamination, the final values used were thus from images with negative sharpness index for magnitudes fainter than 17.5, using the defect/star boundary established, and doubled to account for the real star distribution into positive sharpness values. Table 1 shows the difference, and gives an indication of the compact galaxy counts, which are also of interest.

We stress that for the stars down to magnitude $K \sim 18$ - the range of interest for guiding - we have very well established star/galaxy/blemish separation. The investigation of fainter objects would benefit greatly from images in different colours and with better seeing.

The plot of star counts needs correction for Galactic latitude (and longitude) to the

pole. The factor is derived for the fields from Spagna Fig 11 and a similar plot generated from the Bahcall-Soneira and Besançon models (see below). A correction value of 0.75 was used for both CFHT fields, as an average of these models. The range of all the individual values was about 5%.

The total number of guide stars to our approximate guide signal limits is about 60-100, so there are some small number uncertainties. The two CFHT fields separately give very similar star counts, and Figure 3 combines them. Overall, the star counts to $K=18$ have error bars of 10%. Figure 1 shows the CFHT counts where the values for $K>17$ are free of the probable compact galaxy counts (sharpness > 0 for $K>17.5$). It still appears possible that the galaxy models underpredict faint stars. As the CFHT counts go fainter than shown in the figure, the numbers are given in the Table.

Figure 4 shows the location in one CFHT field of stars bright enough to guide on in the most conservative case ($K=17$), together with the baseline FGS field. This was fudged to some extent: to simulate a Galactic pole field, the magnitude limit used is brighter by the amount that Fig 1 suggests to reduce the star counts by the factor 0.75 - i.e. from 17 to about 16.3. This probably still overestimates the guide star counts but the figure gives a good typical example of a high latitude field and its useable guide stars.

3. Galaxy models

In Figure 3 we also show star counts from other models. We discuss each in the subsections below.

3.1. Spagna report

This report was written to address the NGST guide star availability, and goes into great detail. It is available in full at the website http://www.ngst.nasa.gov/public/unconfigured/doc_0422/rev_03/NGST_GS_report5.pdf. In Figure 3 we show the K-band star counts that are given for the Galactic poles in Table 9 of the report. The model presented is based on that of Mendez and van Altena (1996) and checked by counts from 2MASS and some smaller fields such as the HDF.

The variations with Galactic latitude are shown in Figure 11 of the report, and with longitude in Table 12. These values (and those from Ratnatunga and Bahcall 1985) were used to correct our CFHT field counts to the Galactic pole.

3.2. Bahcall-Soneira model

Ratnatunga and Bahcall (ApJ Suppl 59, 63, 1985) give star counts in V magnitudes, in 3 B-V colour bins, for many positions in the sky, from the Bahcall-Soneira model. The B-V bins (divided at $B-V = 0.8$ and 1.3) correspond to stars of spectral type K0 and earlier, K0 - K8, and K8 and later. Assuming mean spectral types in these bins of F0, K4, and M3, we derive V-K colours of 4.7, 2.5, and 1.4 (Allen 2000). We can thus convert the star counts with V magnitude from Ratnatunga and Bahcall to K-band magnitudes. These are shown in Figure 3. The unknown distribution of spectral type, particularly among faint M stars, makes these model numbers less reliable than the others shown.

These colour conversions show that all spectral types give about the same FGS signal at the same K-band magnitude, which is consistent with the weighted spectral response for the FGS detectors in the 0.7 to 2.5 micron wavelength range. The J-band magnitudes are also similar for the same reason. Thus, counting stars in the J, H, or K bands is a

reasonable way to estimate guide star availability, whereas visible magnitudes have a strong dependence on spectral type. For this reason, catalogues in wave bands below 1 micron are not useful for NIR guide star selection.

The plot in Fig 3 shows the sum of all stars with K-band magnitudes for a few values, using the above corrections. While this model does give important detail on the colour distribution of stars, the conversion to K-band involves some assumptions, as noted above.

3.3. The Besançon model of population synthesis

The numbers presented in Figure 3 have been computed from a revised version of the Besançon model of population synthesis. Previous versions and the main principles were described in Bienaymé et al. (1987a, 1987b) and Haywood et al. (1997). Updates of the thick disk and spheroid parameters are given in Robin et al. (2000) and Reylé & Robin (2001). The principles are briefly recalled below.

Model principles. The model is based on a semi-empirical approach, where physical constraints and current knowledge of the formation and evolution scenario of the Galaxy are used as a first approximation for the population synthesis. The model involves 4 populations (disk, thick disk, halo and bulge), each with specific treatment.

A standard evolution model is used to produce the populations, based on a set of usual parameters : an initial mass function (IMF), a star formation rate (SFR), a set of evolutionary tracks and a metallicity distribution. A set of IMF slopes and SFRs have been tentatively assumed and tested against star counts. The evolutionary model fixes the distribution of stars in the space of intrinsic parameters : effective temperature, gravity, absolute magnitude, mass and age. These parameters are converted into colours in various systems through stellar atmosphere models corrected to fit empirical data (Lejeune et al

1997, 1998).

The disk scale heights have been computed self-consistently from Poisson and Boltzmann equations, using the potential computed from the Hipparcos constraints on the local dynamical mass from Cr     et al (1998). So the disk scale heights are not free parameters, contrary to most galactic models, and are a function of age.

The thick disk and spheroid populations. In the population synthesis process, the thick disk and spheroid populations are modeled as originating from a single epoch of star formation. Bergbusch & Vandenberg (1992) oxygen enhanced evolutionary tracks are used, with mean metallicities of -0.7 and -1.7 dex, and ages of 11 Gyr and 14 Gyr, respectively. Their density laws and IMF have been determined by model-fitting to remote star counts from large data sets in the visible and near-infrared (Robin et al. 2000, Reyl     et al, 2001).

3.4. 2MASS survey data

The 2MASS survey is not as deep as we need but does cover large amounts of sky, and is useful as a check of the brighter star counts. Jean-Francois Le Borgne of the CFHT group sent numbers based on the entire 2MASS database for Galactic latitudes greater than 80° . We obtained a smaller 2MASS dataset (800 sq arcmin) and performed the measurements using the same DAOPHOT software as for the CFHT data (see the plot in the lower panel of Figure 1).

With the same star-galaxy separation software in DAOPHOT, our counts agree with the 2MASS point source catalogue (as also noted by Spagna). The 2MASS-based counts from Le Borgne appear to include all sources in the images without star/flare separation (as we verify from the raw 2MASS images) and we regard them as too high. The star-separated 2MASS counts are shown in Fig 3 as a single set of symbols, and it is clear that they do not

go faint enough to be useful, but agree with the other values as far as they go.

4. Discussion

Overall, there is good agreement in Fig 3 on the star counts in the range where the interest lies for guiding. Current performance modelling for the NGST fine guidance camera suggests using stars down to the range of $K=17.0$ to $K=17.8$. The Spagna and Robin models agree very closely in the range of interest in this context. They diverge at fainter magnitudes, but neither approaches the numbers indicated by the CFHT data.

Colour information on the stars present at these faint magnitudes is needed to determine which population is not well reproduced by the models. Star counts being dominated by M dwarfs, it is probable that the discrepancy comes from the assumed IMF at low masses for old populations.

The NGST Fine Guidance System has a nominal field of view of 8.4 square arcminutes. The star count estimates error on the worst number ($K=17$) gives a count in this FGS field between 3 and 4. 3 stars are the average count required for 95% probability of finding one, and this is the lowest number in all the above estimates. The plot allows estimates of the field size required once the limiting guide signal is known, and converted to NIR band magnitude for the telescope and detector system being used. As a guide to this, we have developed a website that allows signal estimates for a variety of parameters. This is at <http://astrowww.phys.uvic.ca/~gwyn/ngst/phot.html>.

We will need to consider whether a new Galactic pole survey should be undertaken to provide a catalogue of guide stars suitable for NGST. The survey clearly needs to be done in the H or K band, since the V-K corrections for M stars (the most common ones at $K=18$) are in the range of 5 magnitudes, and change rapidly with spectral type among such stars.

5. Acknowledgements

This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

We thank Jerry Kriss for useful discussion on some of this work, Mark Brodwin for participating in the CFHT observations, and Jean-Luc Beuzit for communicating some of the earlier model results.

References

- Allen’s astrophysical quantities, editor Arthur Cox, Springer-Varlag, 2000
- Bergbusch, P. A. & Vandenberg, D. A., 1992, ApJS, 81, 163
- Bienaymé, O., Robin, A. C., Crézé, M., 1987a, A&A, 180, 94
- Bienaymé, O., Robin, A. C., Crézé, M., 1987b, A&A, 186, 359
- Crézé, M., Chereul, E., Bienaymé, O., Pichon, C., 1998, A&A, 329, 920
- Haywood, M., Robin, A. C., Crézé, M., 1997, A&A, 320, 440
- Lejeune T., Cusnier F., Buser R., 1997, A&AS, 125, 229
- Lejeune T., Cusnier F., Buser R., 1998, A&AS, 130, 65
- Mendez R. A., and van Altena W. F., 1996, AJ, 112, 655
- Ratnatunga K. and Bahcall J.A., 1985, ApJS, 59, 63
- Reylé, C. & Robin, A. C. 2001, A&A, 373, 886
- Robin, A. C., Reylé, C., Crézé, M., 2000, A&A, 359, 103
- Stetson, P. B., 1987, PASP, 99, 191
- Stetson, P. B., and Harris, W. E., 1988, AJ, 96, 909

Captions to figures

1. Upper: Image sharpness criterion with K band magnitude for CFHT photometry. The dashed lines outline the locus of star/galaxy/noise separation. To the limit of guide star magnitude (17.8), the sample is very complete and the star/galaxy separation fully verified by inspection. Lower: the same for the 2MASS Galactic pole images.

2. Part of the CFHT field and the same area with 2MASS, both in K-band. The field size shown is close to the nominal NGST FGS field in area, although it is a little more elongated. The faintest stars easily visible in the CFHT field are $K \sim 20$, and in the 2MASS field $K \sim 15$.

3. Plot of total star counts at the Galactic pole per nominal 8.4 sq arcmin FGS field, to K-band limiting magnitudes shown, for the various models and the CFHT photometry. The nominal NEA goal of 3mas is met with the current assumptions about the NGST telescope, and the current understanding of the two detectors, with the magnitude limits shown. 95% probability of a single GS availability require an average of 3 stars per field.

4. One of the CFHT fields outlined, with the positions of $K < 16.3$ stars (equivalent to $K = 17$ counts at the Galactic pole star densities). The FGS nominal field of view is shown for comparison.

Table 1. CFHTIR faint object counts
per 8.4 sq arcmin

to K mag	#objects	#stars
18	7.4	5.1
19	21	9.4
20	46	22
20.5	55	33